A western Pacific oscillator paradigm for the El Niño-Southern Oscillation

Robert H. Weisberg and Chunzai Wang

Department of Marine Science, University of South Florida, St. Petersburg, Florida

Abstract. A data-based hypothesis is presented on the mechanism of the El Niño-Southern Oscillation (ENSO), a major determinant of interannual global climate variability. The hypothesis emphasizes the importance of off-equator sea surface temperature and sea level pressure variations west of the dateline for initiating equatorial easterly winds over the far western Pacific. These winds compete with westerly winds over the equatorial central Pacific enabling the coupled ocean-atmosphere system to oscillate. Consistent with this hypothesis, an analogical oscillator model is constructed that produces ENSO-like oscillations. The proposed mechanism differs from the delayed oscillator paradigm in that wave reflection at the western boundary is not a necessary condition for the coupled ocean-atmosphere system to oscillate.

Introduction

Tropical ocean-atmosphere interactions associated with the El Niño-Southern Oscillation (ENSO) are recognized as being a dominant mechanism for the earth's interannual climate variability [Philander, 1990]. Two paradigms have been proposed for interpreting ENSO-like oscillations, both dependent upon the equatorial waveguide: the slow mode [Hirst, 1988; Neelin, 1991] and the delayed oscillator [Suarez and Schopf, 1988; Battisti and Hirst, 1989]. Slow mode behavior shows systematic, slow eastward or westward propagation. Observed interannual sea surface temperature anomalies, however, do not generally evolve in this manner, thus limiting the usefulness of the slow mode in explaining nature's ENSO [Cane, 1992]. The delayed oscillator paradigm depends upon a delayed negative feedback owing to free oceanic equatorial wave propagation. Growing anomalies in the central Pacific generate Rossby waves which, upon reflection at the western boundary as Kelvin waves, result in a perturbation of opposite sign that eventually counteracts and reverses the originating anomalies in the central Pacific. This mechanism requires that the delay time, associated with wave propagation and reflection, be sufficiently long for the system to oscillate [Battisti and Hirst, 1989]. Observational evidence for the delayed oscillator theory remains equivocal.

Evidence for the Conceptual Model

Under normal conditions atmospheric convection in the vicinity of the equator is most intense over the western Pacific warm pool region, whereas during El Niño the region of convection moves eastward into the west-central Pacific. Consistent with this eastward displacement, the region of anomalous ocean to atmosphere heat flux is observed to expand eastward from the western Pacific into the west-central Pacific during the transition from La Niña to El Niño conditions [Weisberg and Wang, 1997]. Outgoing long-wave radiation and surface wind anomalies are also observed to be maximum in the west-central Pacific [Deser and Wallace, 1990]. Using observed winds, Zebiak [1990] derived a surface pressure field and a dynamically adjusted wind field to infer condensation heating from an atmospheric model similar to Gill's [1980]. Atmospheric heating was found to be maximum in the west-central Pacific during the mature phase of El Niño, in agreement with outgoing long-wave radiation observations. The equatorial west-central Pacific is therefore characterized by large interannual anomalies in the surface fluxes of heat and momentum and in atmospheric heating.

To the east and west of this region COADS data analyses for the period 1950-1992 show distinctively different patterns for the correlation field between SST and SLP, as shown in Fig. 1. East of the dateline is a broad region of negative correlation, centered on and symmetric about the equator. West of the dateline are patterns of symmetric, negative correlation, but located 10°-15° poleward from the equator and separated by a region of positive correlation on the equator. The broader meridional scales observed relative to an oceanic equatorial Rossby radius of deformation are consistent with an ocean-atmosphere coupling-induced wind stress curl [Wang and Weisberg, 1996]. Since the west-central equatorial Pacific condensation heating maximum separates these eastern and western regions during the mature phase of El Niño [Deser and Wallace, 1990; Zebiak, 1990], the patterns may be explained on the basis of a Gill atmosphere. The response to condensation heating shows a region of low pressure extending eastward and symmetric about the equator in the form of a forced Kelvin wave and a symmetric pair of low pressure, off-equator cyclones located just west of the heating in the form of a forced Rossby wave. The Kelvin wave portion of the atmospheric response together with the oceanic response to anomalous westerly wind stress in the west-central Pacific can account for the negative SST/SLP correlation pattern observed in the east. The positive wind stress curl of the off-equator cyclone pair raises the ocean thermocline by Ekman pumping and cools SST, thereby accounting for the off-equator negative SST/SLP correlation pattern observed in the west. Such Ekman pumping and pattern expansion over the western Pacific has been reported [White et al., 1989; Kessler, 1990]. Moreover, time series of these western Pacific, off-equator SST and SLP anomalies show that SST leads SLP [D. Mayer and R. Weisberg, in preparation], suggesting a causal relationship. Arguing again from the vantage point of a Gill atmosphere, the relatively high off-equator SLP resulting from the relatively low off-equator SST initiates easterly winds over

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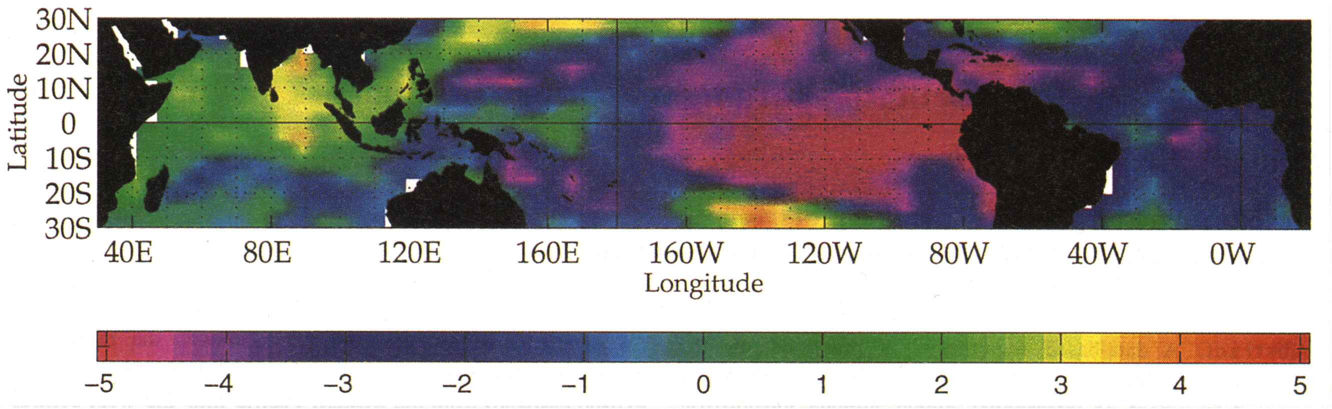

Figure 1. Normalized, zero-lag cross-correlation between interannual anomalies of sea surface temperature (SST) and sea level pressure (SLP) computed globally from 30°N to 30°S [D. Mayer and R. Weisberg, in preparation]. Normalization is by an integral time scale determined standard error, so that values greater than 2.6 exceed a 99% significance level [e.g., Sciremammano, 1979].

the far western Pacific as observed towards the end of El Niño warm phases [Tang and Weisberg, 1984; Deser and Wallace, 1990; Zebiak, 1990; Chao and Philander, 1993]. As these easterlies evolve, with their fetch expanding eastward from the western boundary, they force an ocean upwelling response that proceeds eastward along the equator acting to reverse the sign of the central Pacific NINO3 region SST anomaly and hence the sign of all related variables.

The above sequence of observational facts suggests a conceptual model in which the off-equator western Pacific SST/SLP correlation pattern provides a negative feedback necessary for the coupled ocean-atmosphere system to oscillate. Positive SST-zonal wind stress feedback [Philander, 1990] causes the region of maximum condensation heating, initially in the west, to migrate eastward into the west-central Pacific. In accordance with a Gill atmosphere, an equatorial heating anomaly results in a pair of off-equator cyclones that drive an equatorial westerly wind anomaly. As a result of westerly winds the thermocline depth and SST increase in the central and eastern Pacific. Simultaneously, the off-equator cyclones, via Ekman pumping, cause the off-equator thermocline depth and SST to decrease in the western Pacific, thereby enhancing the off-equator high SLP anomalies there. As a result of off-equator high SLP, once the region of condensation heating moves sufficiently far east into the west central Pacific, equator convergent winds are generated in the far western Pacific that turn anticyclonically to become easterly on the equator. These easterly winds initiate an upwelling thermocline response that evolves eastward along the equator tending to raise the thermocline and decrease SST in the NINO3 region, while deepening the thermocline in the west. As a result of deepening in the west, SST increases and the region of maximum convection is reestablished in the western Pacific.

This conceptual, data-based model differs from the delayed oscillator in that western Pacific easterly winds are an important element for the coupled system to oscillate. Instead of an upwelling Kelvin wave reflecting at the western boundary upon the incidence of a remotely forced upwelling Rossby wave, this mechanism relies upon a locally forced response, initiated by off-equator processes, that emanates from the western boundary. As conceived, the movement of convection eastward into the west-central Pacific during the mature phase of El Niño is thus limited by these western Pacific off-equator patterns that set up in the wake of the eastward moving convection. The western boundary in conjunction with the off-equator processes thus sets the scale over which convection can move eastward before being drawn back as a result of easterly winds in the western Pacific.

Analogical Oscillator Model

As described, the western and west-central Pacific are hypothesized as being causal regions for ENSO. The element enabling the coupled system to oscillate is the off-equator high SLP anomaly pattern that initiates easterly winds over the western equatorial Pacific, providing a negative feedback to reverse the sign of the equatorial central Pacific SST anomaly. It is possible to design an analogical model that includes the basic physics of the hypothesis described above. A schematic diagram of the conceptual model is illustrated in Fig. 2. The analogical model requires four variables, expressed as anomalies from their mean states: equatorial thermocline thickness, h_1 in the NINO3 region, equatorial westerly wind stress, τ_1 in the west-central Pacific, off-equator thermocline thickness, h_2 in the western Pacific, and equatorial easterly wind stress, τ_2 in the western Pacific. The four analogical equations relating these variables are:

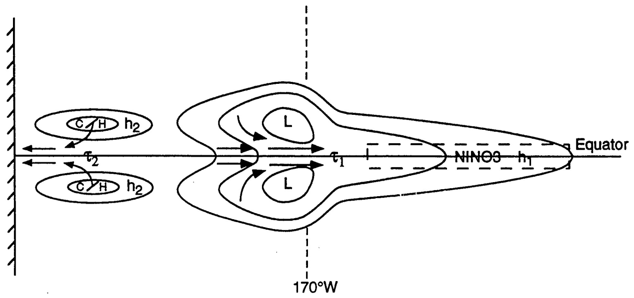

Figure 2. Conceptual model schematic. Condensation heating in the west-central Pacific results in an off-equator cyclone pair and equatorial westerly wind stress, τ_1 that deepens the thermocline, h_1 in the NINO3 region. These cyclones raise the western Pacific off-equator thermocline, h_2 via Ekman pumping, resulting in low SST and high SLP by air-sea interaction. This off-equator high SLP then initiates equatorially convergent easterly wind stress, τ_2 in the far western Pacific that causes upwelling to evolve eastward, providing the negative feedback for the system to oscillate.

$$\frac{dh_1}{dt} = a\tau_1 + b\tau_2(t-\delta) - \varepsilon_1 h_1^3, \quad (1)$$

$$\frac{dh_2}{dt} = - c\tau_1(t-\lambda) - \varepsilon_2 h_2^3, \quad (2)$$

$$\frac{d\tau_2}{dt} = dh_2 - \varepsilon_3 \tau_2^3, \quad (3)$$

$$\frac{d\tau_1}{dt} = eh_1 - \varepsilon_4 \tau_1^3, \quad (4)$$

where t represents time and all constants are positive.

During the mature El Niño phase of ENSO, with convection extending eastward into the west-central Pacific, westerly winds are maximum there, and this deepens the thermocline in the NINO3 region as represented by the first term in Eq. (1). The second term in Eq. (1) represents the negative feedback produced by easterly winds initiated over the far western Pacific. Since it takes time for the western Pacific easterly winds to affect the thermocline in the NINO3 region, a delay, δ is incorporated. The corollary off-equator response is a shoaling thermocline by Ekman pumping in the western Pacific. This process is represented by Eq. (2), with a delay, λ to account for the time taken to affect SST and then SLP. Eq. (3) relates the initiation of easterly winds in the equatorial western Pacific to this western Pacific off-equator thermocline response. The system is closed by Eq. (4) that relates the equatorial westerly winds in the west-central Pacifc to the thermocline thickness in the NINO3 region. The cubic terms represent damping processes that limit anomaly growth.

Solving Eqs. (1)-(4) numerically results in time series for h_1, h_2, τ_2, and τ_1 as shown in Fig. 3, with model parameters: $a=1.5\times10^3$ m^3 N^{-1} $year^{-1}$, $b=9.0\times10^3$ m^3 N^{-1} $year^{-1}$, $c=1.5\times10^3$ m^3 N^{-1} $year^{-1}$, $d=3.0\times10^{-3}$ N m^{-3} $year^{-1}$, $e=3.0\times10^{-3}$ N m^{-3} $year^{-1}$, $\varepsilon_1=\varepsilon_2=1.0\times10^{-2}$ m^{-2} $year^{-1}$, $\varepsilon_3=\varepsilon_4=7.0\times10^2$ m^4 N^{-2} $year^{-1}$ and $\delta=\lambda=30$ days. These parameters give model oscillations with a period of 4.1 years. The relative phasing of the solutions follows that of the conceptual model, i.e., the NINO3 region thermocline thickness, h_1 leads the west-central Pacific wind stress, τ_1, which leads the western Pacific off-equator thermocline thickness, h_2, which leads the western equatorial Pacific wind stress, τ_2. This model, although simple, demonstrates that the data-based ENSO paradigm can produce periodic solutions on interannual time scales.

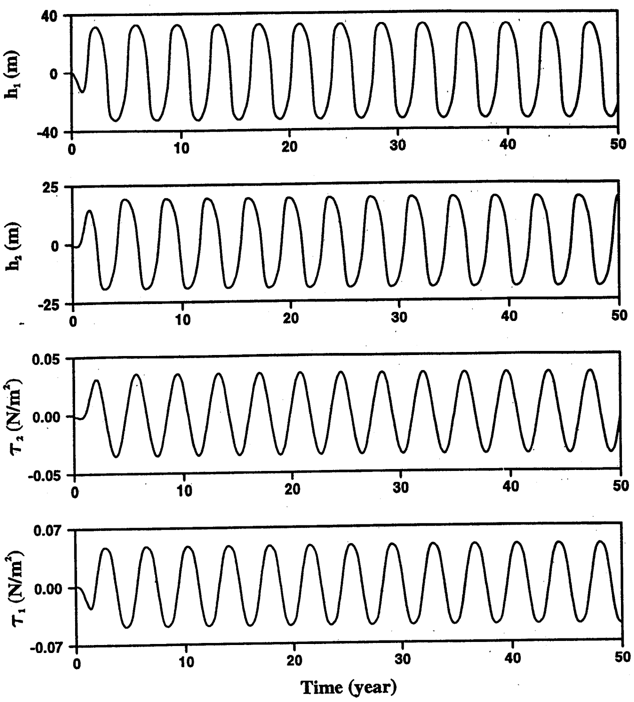

Figure 4. As in Fig. 3 except without time delays.

While Eqs. (1)-(4) contain delay times, such delays are not necessary for the model to oscillate. Fig. 4 shows a solution with the model parameters as in Fig. 3 except that the delays are set to zero. With or without delays the model oscillates in a qualitatively similar manner. To understand why this occurs an analytical solution may be obtained upon omitting in Eqs. (1)-(4) the cubic damping terms and the delays. Reducing these four linear equations to a single equation in τ_1 gives a fourth order differential equation:

$$\frac{d^4\tau_1}{dt^4} - ae\frac{d^2\tau_1}{dt^2} + bcde\tau_1 = 0, \quad (5)$$

that has a general solution of the form:

$$\tau_1 = C_1 e^{(A+iB)t} + C_2 e^{-(A+iB)t} + C_3 e^{(A-iB)t} + C_4 e^{(-A+iB)t}, \quad (6)$$

where the C's are arbitrary constants, $i = \sqrt{-1}$, and

$$A = \sqrt{R}\cos(\theta/2), \ B = \sqrt{R}\sin(\theta/2), \quad (7)$$

$$R = \sqrt{bcde}/2, \ \theta = \tan^{-1}\left(\sqrt{4bcde - a^2e^2}/ae\right). \quad (8)$$

Oscillatory behavior occurs for $a^2e<4bcd$, which helps to explain the nature of the oscillations. The parameters a and e relate τ_1 to the NINO3 region h_1, a positive feedback, while the parameters b, c and d relate h_1 to the western Pacific off-equator processes, a negative feedback. It is the competition between these central and western Pacific processes that enables the system to oscillate without explicit time delay. The frequency of oscillation is equal to B, which for the above parameters gives a period ($2\pi/B$) of 4.2 years in agreement with the previous numerical solutions.

Even in the simplest case of no dissipation or delays, the system depends upon five parameters. These parameters for

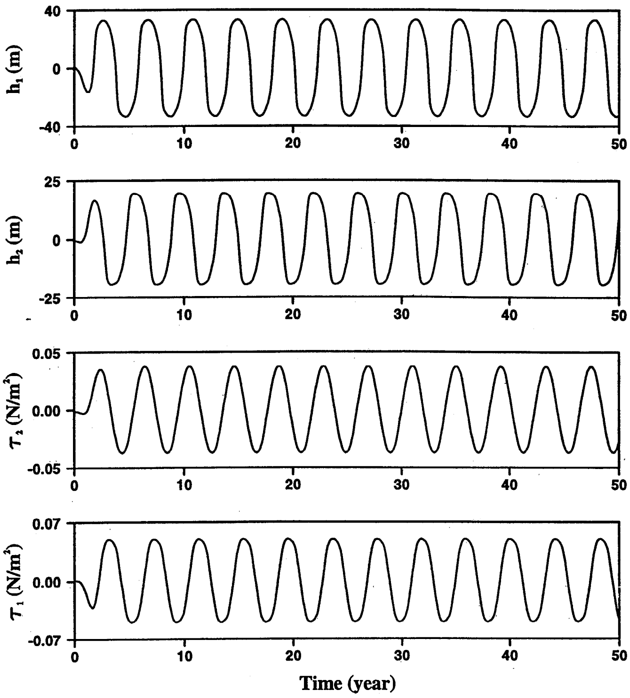

Figure 3. Numerical solutions of Eqs. (1)-(4) with the model parameters given in the text.

the above example were chosen by non-dimensionalizing the equations and choosing scales for h_1 consistent with a balance on the equator between the zonal pressure gradient and the zonal wind stress and for h_2 consistent with an off-equator wind stress curl-induced Ekman pumping. Parameter values were then assigned by letting all of the terms be approximately the same size, noting that in nature both the wind stress magnitude and its fetch are important in accounting for the thermocline adjustment. Choosing parameters in this way gave a result compatible with ENSO. However, the period of oscillation is parameter dependent and the system can oscillate over a wide range of parameter values ($a^2e<4bcd$). Since in nature, these parameters cannot be expected to be constants, even this simple model suggests that the ENSO cycle should be irregular, as observed.

Summary and Discussion

Motivated by a conceptual data-based hypothesis on the mechanism of ENSO, an analogical oscillator model of the coupled tropical Pacific ocean-atmosphere system is constructed. The model considers the thermocline thickness in the equatorial Pacific NINO3 region, the equatorial zonal wind stress in the west-central Pacific, the off-equator thermocline thickness in the western Pacific, and the equatorial zonal wind stress in the western Pacific. Arguing from the vantage point of a Gill atmosphere, condensation heating due to convection in the west-central Pacific induces a pair of off-equator cyclones with westerly wind anomalies on the equator. These westerly winds act to deepen the thermocline and increase SST in the NINO3 region, thereby providing a positive feedback for anomaly growth. On the other hand, the off-equator cyclones raise the thermocline there via Ekman pumping. Thus, a shallow off-equator thermocline anomaly expands over the western Pacific leading to a decrease in SST and an increase in SLP. During the mature phase of El Niño, off-equator high SLP initiates equatorial easterly winds over the far western Pacific. These easterly winds cause upwelling that proceeds eastward as a forced ocean response providing a negative feedback necessary for the coupled ocean-atmosphere system to oscillate. The easterlies also deepen the thermocline in the western Pacific, effectively drawing back the region of maximum convection that had moved into the west-central Pacific during the mature phase of El Niño. With parameters chosen on physical grounds, the model oscillates with a period of about 4.1 years, consistent with observations. Unlike the delayed oscillator paradigm, delay parameters are not necessary for this model to oscillate. It is the competition between the equatorial central and off-equatorial western Pacific thermocline responses that enables the system to oscillate. Thus, this new oscillator paradigm does not require wave reflection at the western boundary.

Compared with the solution of Eqs. (1)-(4), ENSO variability in nature is known to be irregular. The introduction of random atmospheric forcing to an otherwise perfectly periodic system can lead to irregular or chaotic oscillations [e.g., Graham and White, 1988] as can nonlinearity [Munnich et al., 1991], or interactions between annual and interannual cycles [e.g., Tziperman et al., 1994]. There may be many reasons for ENSO irregularity, but even for a simple system of linear equations, the recognition that nature does not provide a constant parameter medium also leads to irregularity.

With different mechanisms capable of producing ENSO-like oscillations, more than one may be operant in nature. Thus, while the delayed oscillator mechanism has demonstrated predictive capability [e.g., Zebiak and Cane, 1987], the western Pacific mechanism presented here may also be a factor. If this is true then the inclusion of multiple mechanisms into more complete models may result in improved predictions. For example, we can speculate that the inclusion of easterly winds over the western Pacific into present predictive schemes would tend to improve the estimation of the La Niña phase of ENSO. Retrospectively, the phasing of a forced ocean thermocline response in the eastern Pacific by easterly winds over the western Pacific during the 1982/1983 El Niño [Tang and Weisberg, 1984] is consistent with this.

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Robert H. Weisberg and Chunzai Wang, Department of Marine Science, University of South Florida, 140 7th Avenue South, St. Petersburg, FL 33701. (e-mail: weisberg@ocg6.marine.usf.edu; wang@ocg6.marine.usf.edu)

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